Sustainability Assessment of Industrial Systems

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Sustainability is a vital issue for long-term development of industries and effective environmental protection. The principal aim of sustainable development is the progress on all fronts, i.e., economy, environment, and society. In this paper, a set of new sustainability indices is introduced to assess the environmental and economic performances as well as the sustainability of industrial systems in a uniform structure. In these indices, the values of nonmoneyed and moneyed resources, services, and commodities are quantified using a common unit: emergy. As compared to the existing emergy-based sustainability indices that originated from the study on agricultural or natural ecological systems, the newly defined indices improve the applicability and the effectiveness of the existing indices by addressing the unique features of industrial systems systematically. These new indices reveal strong interdependence among multiple objectives and provide clear guidance to the industries on how to improve their performance on multiple fronts. The utilities of the new indices are demonstrated by case studies.

Introduction

Sustainability is a vital issue for long-term development of industries and effective environmental protection. Sustainable development can be defined as the development in which the needs of the present generation are met without compromising the ability of future generations to meet their requirements. The principal aim of sustainable development is the progress on all fronts, i.e., economy, environment, and society.[1]

A number of environmental performance assessment techniques are available, such as AIChE total cost assessment,[2] life cycle analysis,[3] and integral biodiversity impact-assessment system.[4] These techniques address the environmental impacts of a system from different angles. However, in this challenging world, the economic profitability of the industry needs to be well addressed simultaneously.

A number of sustainability assessment methods have also been developed and widely accepted. Ulgiati et al.[5] introduced a set of general sustainability indices based on the study of agricultural systems. This suggests considering more details in assessing industrial systems.[6−8] The AIChE sustainability index metric (SIM) is an excellent method of measuring the sustainability of an industry. It is formed based on the ratios of different process streams in plants.[9] The streams bearing environmental impacts, such as resource consumption and/or pollutant waste, are represented in the numerator, while the outputs of the process in physical or financial terms are represented in the denominator. If all quantities in the numerator and the denominator are normalized to per pound of product, then a number of metrics can be formed to indicate economic, environmental, and social sustainability of the process. To combine the economic and environmental performances of an industrial process, the AIChE SIM uses six indicators, i.e., material intensity, energy intensity, water consumption, toxic emissions, pollutant emissions, and greenhouse gas emissions. However, different units of these indicators may cause difficulty in evaluating the overall sustainability.

The growth and development of ecosystems is determined by the availability of energy and the ability of organisms to convert it to useful work. As a given amount of the available energy moves from lower to higher organisms, its quality improves but its quantity decreases. Thus, the ecological cost of nature's products and services may be estimated as the amount of energy used directly or indirectly in its manufacture, which is named emergy.[10] In this paper, a new set of indices is introduced to quantitatively assess the environmental and economic performances as well as the sustainability of industrial systems. In these indices, the values of nonmoneyed and moneyed resources, services, and commodities are effectively quantified using a common unit, emergy, which provides a uniform framework for the evaluation of the environmental performance and the sustainability of industries. As compared to the existing emergy-based sustainability indices that were developed from the study of agricultural or natural ecological systems, the new indices are devised by addressing the unique features of industrial systems, i.e., waste treatment, recovery, reuse, and recycle. By considering all of the material/energy flows and investments in industrial systems, the applicability and effectiveness of the emergy-based indices in analyzing industrial systems can be improved significantly.

The concept of industrial ecology is a valuable aspect of sustainable engineering. Industrial ecology can be defined as the study of physical, chemical, and biological interactions and interrelationships within and between industrial and ecological systems.[11] An industrial ecosystem is analogous to a natural ecosystem where organisms survive by consuming other organism's product/waste, so that no source of energy is wasted. Similarly, in an industrial ecosystem, industries come together in such a manner that the product/waste generated by one industry is used as a resource by another industry. The aim of an industrial ecosystem is to change the industrial process from a linear one to a cyclic one so that the waste from one industry is used as an input for another. This system structure results

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in strong interdependence among the member entities. Therefore, the performance of each entity in an ecosystem will be partially determined by the activities of other entities. These new indices can be a valuable tool in revealing the interdependence among the member entities in achieving the economic, environmental, and sustainability goals.

In an industrial ecosystem, the member industries can improve their economic and environmental performance by discovering the opportunities for internal recycle and external mass/energy exchange and exploring market opportunities for waste. These not only help to improve the economic status of the industry by cutting down the requirement of fresh resources but also reduce environmental pressure by reducing the amount of waste disposed of and the consumption of fresh nonrenewable resources.

On the basis of these principles, several industrial ecoparks have been developed around the world. The industrial complex in Kalundburg, Denmark, is an example of such an industrial ecosystem. In that example, five different industries together formed a highly integrated industrial system that optimized the use of its byproducts, thereby minimizing the amount of net waste disposed of.[11] Consequently, the sustainability of the industrial system was improved. Another example is the Dalian Economic and Technological Development Zone, China, which has around 1150 enterprises with over U.S.$10 billion investment. In that park, air emission control, water management, solid waste management greener technologies, and cleaner production processes were implemented.[12] Several such industrial ecoparks and resource recovery parks are now being developed in the U.S., for example, Cabazon Resource Recovery Park, Mecca, CA, Urban Ore Resource Recovery Park, San Leandro, CA, and The Brownsville Project, Brownsville, TX.[13] Apart from such ecoparks, several industrial complexes also exist around the world implementing internal and external recycle to minimize waste discharge. For example, the Mississippi River Corridor Industrial Complex comprises around 150 chemical plants. Significant research activities have been directed toward minimizing waste disposal and maximizing material and energy reuse in this complex.[14] Governments and industries around the world tried in many ways to promote research and business opportunities in industrial sustainability and external recycling.[15] In the U.S., many different sources, including federal, state, and local governments, industry, professional associations, universities, and nongovernmental organizations, have acknowledged the importance of sustainability and support the research and business opportunities at various levels.[16]

In the case of an industrial ecosystem, the individual performances as well as the performance of the entire system need to be addressed clearly. When the fundamentals are revealed, the newly introduced indices provide a clear guidance to the industries on how to improve the economic, environmental, and sustainability performance of individual industries as well as the entire industrial ecosystem.

Basics of Emergy Analysis

The theory of environmental accounting through emergy analysis is based on the evaluation of the energy used for making products or services. This “used” energy is called emergy.[10] In other words, emergy is the available energy of one kind previously required, directly and indirectly, to make the products or services. The unit of emergy is emjoule. To calculate the emergy of a particular substance or service, transformity of that substance or service will be needed. Transformity is defined as the emergy of one kind of available energy required to make 1 J of energy of another type.[17] The unit of transformity is solar emjoule per joule when emergy is calculated in terms of solar energy. In case the transformity is unknown, the emergy/money ratio is helpful in calculating the emergy of the substances or the services. Emdollars, i.e., the ratio of emergy to money, is calculated by dividing the total emergy use of a country by its gross economic product.[10]

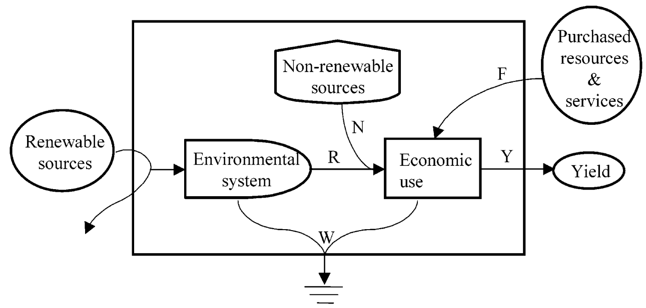

Figure 1. Traditional emergy-flow diagram. Reprinted from ref 17, Copyright 1998, with permission from Elsevier.

Emergy analysis provides a common platform to quantitatively express the economic values as well as the environmental factors. It facilitates the comparison of the economic and environmental status of different industrial entities on a common ground. Hence, the sustainability performance can be exploited conveniently.

Traditional Emergy-Flow Diagram and Emergy Indices

In traditional emergy-flow analysis as shown in Figure 1, the natural renewable resources (R; such as water, air, and solar energy) and nonrenewable resources (N; such as fossil fuels) are consumed through purchased resources (such as equipment) and services (such as labor) (F) for economic use. As a result, yield (Y) is generated along with waste (W), i.e., undesirable byproduct. Yield (Y) will be sold in the market and waste (W) will be disposed of to the environment.

On the basis of this emergy-flow diagram, several indices have been developed to quantify the economic, environmental, and sustainability performance of a system.[10,17,18] Those related to this work are reviewed briefly below.

(a) Environmental Yield Ratio (EYR). It is defined as the ratio of emergy of the yield (Y) to the emergy of imported investment (F) required to convert the raw materials to product, i.e., $\mathrm{EYR} = Y/F$. As the definition suggests, a high value of EYR is always desired. Thus, the yield should be high for a given investment, while the investment is expected to be low for any given yield.

(b) Environmental Loading Ratio (ELR). It is defined as the ratio of the sum of the imported emergy (F) and emergy of nonrenewable resources (N) to the emergy of renewable resources (R), i.e., $\mathrm{ELR} = (F + N)/R$. Obviously, a low value of ELR, as an indicator of low environmental pressure, is always desired. Therefore, imported resource or service (F) and the consumption

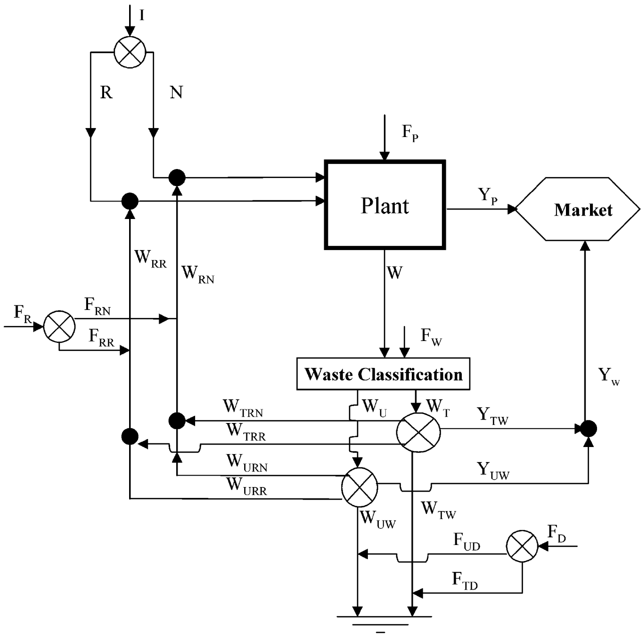

Figure 2. New emergy-flow diagram for an industrial system.

of nonrenewable resources used (N) should be kept low, and the usage of renewable resources should be high.

(c) Index of Sustainability (SI). This index combines both environmental and economic factors that affect the performance of an industry. It is defined as the ratio of EYR to ELR, i.e., SI = EYR/ELR. This index reflects the ability of a system in providing desired products or services with a minimum environmental stress and a maximum profit. Naturally, a high value of SI is always preferred.

Industrial Emergy-Flow (IEF) Diagram and New Emergy-Based Indices

The traditional emergy-flow diagram provides a general framework for depicting the relationships of different components in an ecosystem. However, for an industrial system, a much more detailed portrait of its unique features needs to be fully explored;[7] especially, the fate of waste and the cost associated with waste treatment, recycle, and waste disposal should be fully considered. Figure 2 is an IEF diagram that is to be fully studied.

The IEF diagram encompasses all kinds of possible mass/energy flows of an industrial system. The main difference between the traditional and the new emergy-flow diagram lies in the classification of the waste generated by the process system. For an industrial system, the waste generated during production may either undergo waste treatment (e.g., desulferization and detoxification) as per environmental regulations or remain untreated if harmless. Sometimes, the waste can be recycled internally as a renewable/nonrenewable resource (like wastewater and residual heat). Under some circumstance, it can be exported to other industries, as well as commercial, residential, or agricultural units, to be used as a material/energy resource supplement (e.g., fly ash generated by burning coal in a power plant can be sent to a cement factory as a raw material).

As shown in Figure 2, the fate of waste generated during production (W) is taken into full consideration. Some of the waste can be handled without treatment (W_U), while some needs to be discharged to the environment only after waste treatment (W_T). Part of W_U may be directly discharged into the environment (W_{UW}), part of it may be recycled as a nonrenewable resource (W_{URN}) or renewable resource (W_{URR}), and part can be sold in the market (Y_{UW}). For W_T, some of it may be discharged to the environment after waste treatment (W_{TW}), some can be recycled as a nonrenewable resource (W_{TRN}) or renewable resource (W_{TRR}), and some can be sold in the market (Y_{TW}). W_{TRN} and W_{URN} together are the total amount of waste recycled as nonrenewable resource (W_{RN}). Similarly, W_{TRR} and W_{URR} together are the total amount of waste recycled as renewable resource (W_{RR}). The summation of W_{UW} and W_{TW} gives the total waste discharge (W_w). Y_{UW} and Y_{TW} together are the total waste that can be sold as a useful product (Y_W). The investment of the industrial system can thus be classified into four parts: the investment on production (F_P), waste treatment (F_W), waste recycle (F_R), and waste disposal (F_D). F_R consists of the cost for recycle of nonrenewable resources from waste (F_{RN}) and that for recycle of renewable resources from waste (F_{RR}) including the handling and transportation cost for each of them. F_D also consists of two parts: the cost of disposing treated waste into the environment (F_{TD}) and the cost of disposing untreated waste (F_{UD}).

To provide a more realistic analysis on the environmental, economic, and sustainability performances of industry systems, a set of new emergy indices is developed based upon the IEF diagram.

(a) Index of Economic Performance (IEcP). The index of economic performance is defined as the ratio of the total yield to the total investment needed in obtaining the required quantity of the product of desired quality, while satisfying the environmental regulations, i.e.,

$$\mathrm{IEcP} = (Y_P + Y_W)/(F_P + F_W + F_R + F_D + I)$$

Note that the numerator of IEcP is the sum of the emergy of all of the products produced by a plant, including the products and byproducts (Y_P), and the useful yield obtained from waste (Y_W). The denominator of IEcP is the emergy of the investment for production (F_P) and the waste treatment (F_W), recycle (F_R), and disposal (F_D) under environmental constraints, and resource intake ($I = N + R$). As discussed before, a high value of IEcP indicates a high product yield with less investment, and this is desirable. If the IEcP value of a plant is less than 1, its economic performance is unacceptable. In this case, the following approaches can be considered.

(i) To improve the product yield (Y_P). Improvement in product quality and quantity can be obtained through better product and process design and improved operational strategy. On the contrary, any increase in the production cost (F_P) or resource investment (I) for better yield may adversely affect IEcP. Hence, any attempt to increase the yield should keep the investment as low as possible.

(ii) To convert “waste” to “treasure” (Y_W) economically. Identifying market opportunities for the waste generated will improve IEcP. If some waste can be exported or recycled, it will cut down the waste treatment and waste disposal cost and thus increase IEcP eventually.

(iii) To reduce fresh resource consumption (I). Adopting highly efficient processing techniques will help to improve the yield while using fewer resources. Efficient mass and energy networks for recycling/reuse can also considerably lower the demand on fresh raw material and utility in plants.[19] Through recycle, the net amount of waste discharge will be reduced, so the waste treatment (F_W) and waste disposal cost (F_D) will be decreased correspondingly. All of these will help to improve IEcP. However, the investment on recycle (F_R) should be kept as low as possible to maintain a good economic performance.

(iv) To reduce waste treatment cost (F_W) and waste disposal cost (F_D). Waste reduction or elimination in production can dramatically reduce the need for waste treatment and disposal.[18] The invention and adoption of economically and technically effective waste treatment and disposal technologies will also help to reduce F_W and F_D.

As a rule of thumb, any process that can generate a maximum yield with minimum processing cost is economically attractive. The improvement in the product quality and yield may have a positive effect on the production cost (F_P), resource requirement (I), and waste generation. Hence, there should be an attempt to minimize the overall investment while improving the product yield or its quality. Another approach is to reduce the cost on waste treatment, waste disposal, and recycle or to convert waste to useful merchandise. These can also help to reduce environmental pressure and thus improve sustainability.

(b) Index of Environmental Performance (IEvP). IEvP quantifies the environmental load from a plant. Because the majority of industrial activities consume renewable resources and discharge waste into the environment, a high environmental load is frequent. IEvP is defined as the ratio of the sum of the emergy of nonrenewable (N) resources and the waste released into the environment with or without waste treatment ($W_{UW} + W_{TW}$) to the total emergy of renewable resources used in the plant and the recycle streams for both renewable as well as nonrenewable resources ($W_{RR} + W_{RN}$) in the plant. That is

$$\mathrm{IEvP} = (N + W_{UW} + W_{TW})/(R + W_{RR} + W_{RN})$$

To make the plant environmentally sustainable, IEvP should be kept as low as possible. Any plant relying heavily on nonrenewable resources is not environmentally friendly. The environmental performance of a plant is further degraded if it releases a large amount of waste into the environment. The following strategies are applicable for a plant to reduce IEvP.

(i) To reduce the consumption of nonrenewable resources (N) and to replace them by appropriate renewable resources (R). This can lessen the stress exerted by the plant on the environment. Nevertheless, the increased consumption of renewable resources in the form of raw material and energy may require some process or product modification.

(ii) To minimize the total amount of waste discharge to the environment ($W_{UW} + W_{TW}$) and to improve the recycle and reuse of waste generated by the plant ($W_{RR} + W_{RN}$). The waste discharge from the plant can be reduced through improvement of plant design, operation, and control. An efficient recycling and reuse mechanism within the plant and industrial ecosystem can also effectively reduce waste discharge. If the recycled resource is nonrenewable, it can further reduce the consumption of fresh nonrenewable resources. This again helps to reduce the environmental pressure. Clearly, the increased utilization of renewable resources (R) and improved recycling or reuse of waste (Y_W) can reduce IEvP.

(c) Index of Sustainable Performance (ISP). ISP is defined as the ratio of IEcP and IEvP, i.e.,

$$\mathrm{ISP} = \mathrm{IEcP}/\mathrm{IEvP} = [(Y_P + Y_W)/(F_P + F_W + F_R + F_D + I)]/[(N + W_{UW} + W_{TW})/(R + W_{RR} + W_{RN})]$$

Thus, a higher value of ISP indicates a higher sustainability of the plant. To improve the sustainability, all factors involved in IEcP and IEvP must be analyzed carefully. For example, the net waste discharge can be reduced by generating market opportunities for the waste, adopting efficient recycle networks, and implementing effective and affordable waste treatment technologies. These will reduce the disposal cost (F_D). On the other hand, recycle of waste ($W_{RR} + W_{NR}$) can reduce the environmental stress, i.e., IEvP. However, if the waste treatment cost (F_W) or recycle cost (F_R) is too high, it may decrease the value of IEcP. Thus, the influence of these factors on sustainability may be complicated because of the combined effects on IEcP and IEvP. ISP emphasizes implementing the optimal strategy to improve the sustainability of the industry and eventually the entire industrial ecosystem. It seeks the balance between economic and environmental aspects of the plant by providing proper considerations to the production, waste, and cost factors. Conclusively, the sustainability of a plant can be enhanced in the following ways.

(i) To improve the product yield (Y_P) with no considerable increment in production cost (F_P).[20]

(ii) To improve the yield from the waste (Y_W) with minimum waste treatment cost (F_W).

(iii) To replace the nonrenewable resources (N) with renewable resources (R), while keeping the production cost (F_P) at the minimum level and maintaining product quality.

(iv) To reduce waste generation in production (W), hence reducing the waste treatment cost (F_W) and eventually the waste disposal cost (F_D).

(v) To reduce waste release into the environment ($W_{UW} + W_{TW}$) so that the waste disposal cost (F_D) can be minimized.

(vi) To employ efficient recycle networks ($W_{RR} + W_{RN}$) for reducing the consumption of fresh resources with minimum recycle cost (F_R).

The relationships among the variables in the definition equations for IEcP, IEvP, and ISP indicate possible approaches to improve sustainability of industrial systems. Some of the relationships are already well accepted but have not been validated using sustainability theory yet. The effectiveness of the three indices is justified by those well-accepted practices.

Case Studies

An industrial system of two plants is selected for evaluating the newly introduced emergy-based indices. Three operational modes between the two plants are considered. In case 1, plants 1 and 2 are completely isolated from each other. Neither do they recycle waste internally nor do they sell it to the external market. Case 2 introduces internal waste recycle in each of the two plants. Case 3 demonstrates the concept of an industrial ecosystem where plants 1 and 2 have internal

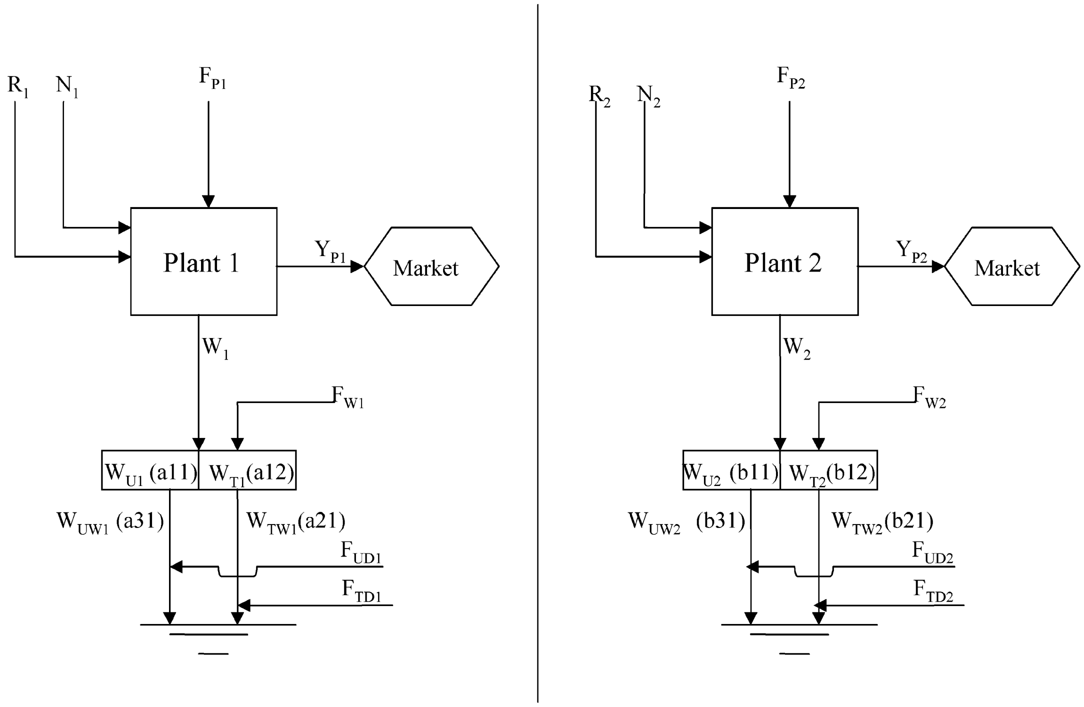

Figure 3. Case 1: isolated plants without internal recycle and waste reuse.

Table 1. Resource and Product Price for Plants 1 and 2

	plant 1 ($/ton)	plant 2 ($/ton)
R	30	50
N	45	80
Y_P	200	400
F_{TD}	10	30
F_{UD}	15	40
Y_{TW}	60 (to plant 2, Y_{TW1})	
Y_{UW}		40 (to plant 1, Y_{UW2A})
	40 (to market, Y_{UW1})	50 (to market, Y_{UW2B})

Table 2. Coefficients for Waste Streams in Plant 1

waste stream	coefficient	case 1	case 2	case 3
W_{U1}	a_{11}	0.2	0.2	0.2
W_{T1}	a_{12}	0.8	0.8	0.8
W_{TW1}	a_{21}	1	0.5	0.2
W_{TRN1}	a_{22}	0	0.5	0.5
Y_{TW1} (to plant 2)	a_{23}	0	0	0.3
W_{UW1}	a_{31}	1	0.7	0.1
W_{URR1}	a_{32}	0	0.3	0.5
Y_{UW1} (to market)	a_{33}	0	0	0.4

recycles by themselves as well as material/energy exchanges between them.

For all of these cases, a mathematical model for each plant is listed in the appendix. The models contain various coefficients to signify material flow ratios when process and waste streams are split. Figures 3−5 depict three cases, where the coefficients (a_{ij} or b_{ij}) are listed. The price of the resources and products for the two plants are given in Table 1. Note that the cost for handing and transporting the marketable waste (Y_{UW} or Y_{TW}) is included in their price. Tables 2 and 3 list the coefficient values for each case of plants 1 and 2, respectively.

Case 1: Isolated Plants without Internal Recycle and Waste Reuse. As shown in Figure 3, case 1 represents a scenario of two isolated plants with neither internal recycle nor external utilization of the waste. The untreated waste streams (W_{UW1} and W_{UW2}) and the treated waste streams (W_{TW1} and W_{TW2}) are discharged into the environment. In this case, the coefficients (a_{21},

Table 3. Coefficients for Waste Streams in Plant 2

waste stream	coefficient	case 1	case 2	case 3
W_{U2}	b_{11}	0.3	0.3	0.5
W_{T2}	b_{12}	0.7	0.7	0.5
W_{TW2}	b_{21}	1	0.2	0.2
W_{TRN2}	b_{22}	0	0.4	0.4
W_{TRR2}	b_{23}	0	0.4	0.4
W_{UW2}	b_{31}	1	1	0.2
Y_{UW2}	b_{32}	0	0	0.8
Y_{UW2A} (to plant 1)	b_{41}	0	0	0.5
Y_{UW2B} (to market)	b_{42}	0	0	0.5

Table 4. Performance Indices of Plant 1 in Three Different Cases

performance index	case 1	case 2	case 3
profit ($/year)	9.591×10^6	1.496×10^7	2.099×10^7
IEcP	1.499	2.082	2.715
IEvP	2.833	0.828	0.359
ISP	0.529	2.513	7.567

a_{31}, b_{21}, and b_{31}) of the streams, W_{TW1}, W_{UW1}, W_{TW2}, and W_{UW2}, are all equal to 1. This indicates that all of the waste generated during production is discharged into the environment.

For plant 1, 80% of its total waste needs to be treated before entering the environment. For plant 2, this amounts to 70% of the total waste. It is clear that the waste treatment cost affects the profit of both plants and the waste discharge exerts a high pressure on the environment. In addition to waste treatment cost, the plants have to pay for waste disposal, the cost of which is proportional to the amount of waste being disposed of. The disposal cost causes a considerabe reduction of the overall profit and hence the IEcP value for both plants.

Another factor that affects the profit and economic performance of both plants is the amount of fresh resources being consumed. The absence of any mechanism for recycling useful material from the waste streams results in excessive consumption of fresh resources that are either from market or the environment. As shown in Tables 4 and 5, both plants have

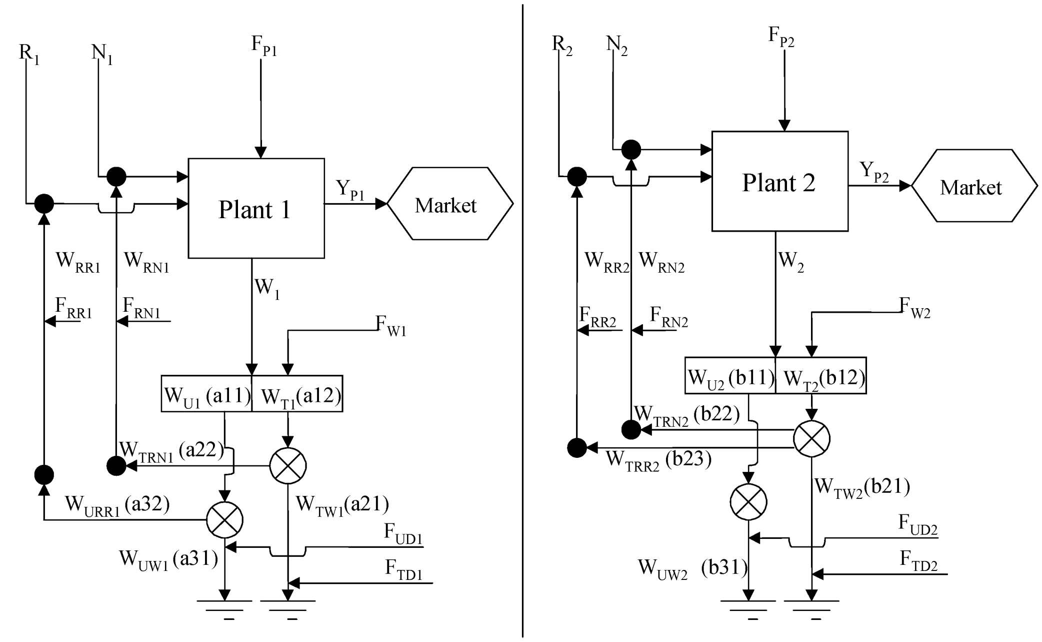

Figure 4. Case 2: isolated plants with internal recycle.

Table 5. Performance Indices of Plant 2 in Three Different Cases

performance index	case 1	case 2	case 3
profit ($/year)	2.342×10^7	3.718×10^7	4.303×10^7
IEcP	1.641	2.630	2.972
IEvP	2.347	0.874	0.603
ISP	0.699	3.009	4.925

maintained good profit ($9.591 $\times$ 10^6/year for plant 1 and $2.342 $\times$ 10^6/year for plant 2) and reasonable values of IEcP (1.499 for plant 1 and 1.641 for plant 2). Their environmental performance based on IEvP is 2.833 for plant 1 and 2.347 for plant 2. This is very poor, which eventually affects the overall performance, as depicted in the their ISP values (0.529 for plant 1 and 0.699 for plant 2).

In this case, the plants are able to maintain their economic performance, which is a prerequisite for their survival, but they have ignored the environmental pressure and thus the sustainability issue. High values of IEvP of these two plants show their inability to recognize the opportunities of waste recovery and recycle. On the other hand, the attempts in the direction of reducing IEvP through reducing waste discharge or recycling may eventually increase IEcP of the plant. However, the extent to which the sustainability performance can be improved also depends on the costs related to waste treatment, recycle, and reuse. Further investigation is needed in order to evaluate the impacts of each of these factors on the sustainability performance.

Case 2: Isolated Plants with Internal Recycle. As shown in Figure 4, the treated and untreated waste streams are now split into recyclable and disposable waste streams. There are two types of recycling streams: W_{RR} as the recycle of renewable resources and W_{RN} as the recycle of nonrenewable resources. In plant 1, part of the treated waste can be recycled as a nonrenewable resource (W_{TRN1}) and part of the untreated waste can be recycled as a renewable resource (W_{URR1}). In plant 2, only treated waste is recycled. Part of it belongs to a renewable resource (W_{TRR2}), while part of it belongs to a nonrenewable resource (W_{TRN2}).

In plant 1, 50% of the treated waste is recycled ($a_{22} = 0.5$), which saves an equal amount of fresh nonrenewable resources. Thus, the disposal of treated waste in plant 1 is now reduced to 50% of its value in case 1 (a_{21} is reduced from 1 in case 1 to 0.5 in case 2). Besides, plant 1 recycles 30% of its total untreated waste in the form of renewable resources ($a_{32} = 0.3$), which also helps to save fresh resources and release environmental pressure. In plant 2, a total of 40% of its treated waste stream is recycled as nonrenewable material ($b_{22} = 0.4$), another 40% are recycled as renewable material ($b_{23} = 0.4$), and the remaining 20% are disposed of into the environment ($b_{21} = 0.2$). Tables 2 and 3 list the coefficients of waste streams for plants 1 and 2 in case 2, respectively (see column 4 of each table). With recycle, the economic and environmental performances of plants 1 and 2 improve significantly, as reflected in the values of the performance indices listed in column 3 of Tables 4 and 5.

The change in the IEcP value is mainly due to the following reasons: a reduction in the investment for fresh resources and a reduction in the investment for waste disposal/treatment. However, now there is an additional cost factor, i.e., recycle cost, that adds to the total investment of the plant. This is the reason the improvement in IEcP is not significant as compared to that in IEvP.

The environmental pressure of both plants is reduced considerably as compared to case 1 because of the following reasons: (i) a reduction of the consumption of fresh nonrenewable resources, (ii) a reduction of the net amount of waste disposal, and (iii) a recycle of nonrenewable and renewable resources.

Finally, a higher IEcP and a lower IEvP contribute to the higher sustainability performance of both plants. As shown in Table 4, ISP of plant 1 is increased by 375% (from 0.529 in case 1 to 2.513 in case 2). Table 5 shows that ISP of plant 2 is increased by 330% (from 0.699 in case 1 to 3.009 in case 2).

Case 3: Plants with Internal Recycle and External Exchange. In this case, plants 1 and 2 explore

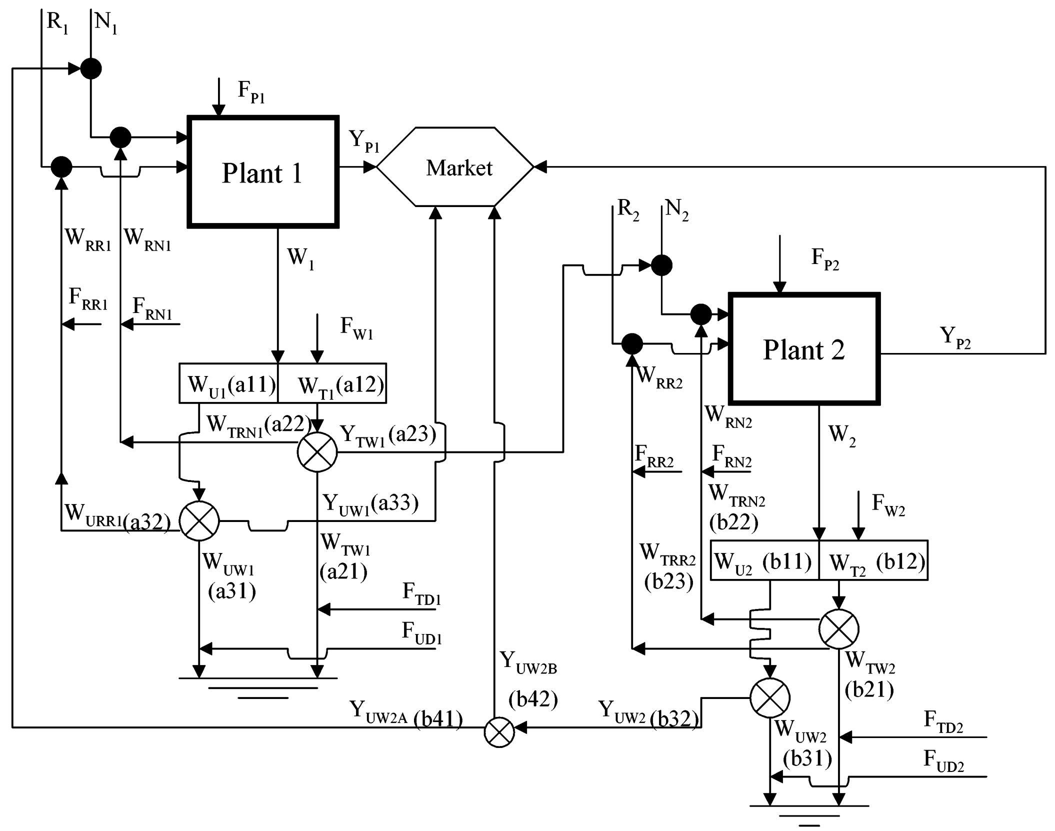

Figure 5. Case 3: plants with internal recycle and external exchange.

the option of finding market opportunities for their waste. A plant may not be able to fully recycle and reuse all of the waste it generates because of material and energy specification, quality purpose, capacity limit, and/or cost issues. However, there is a possibility that other systems may utilize their waste. Under such circumstances, it will be reasonable for these plants to hunt for potential customers who will buy their waste material and waste energy. This can improve the sustainability through improved economic performance and reduce the environmental pressure by reducing the total waste discharged into the environment.

Figure 5 depicts the case of an industrial ecosystem where plants 1 and 2 explore the option of selling their residual waste either to each other or to the market. This helps reduce the consumption of fresh resources. The treated and untreated waste streams from plant 1 are split into three streams: disposable, recyclable, and marketable streams. The marketable streams of the treated or untreated waste for plant 1 are denoted as Y_{TW1} and Y_{UW1}, respectively, and their corresponding coefficients are a_{23} and a_{33}.

In this case, plant 1 sells 30% of its total treated waste to plant 2 ($a_{23} = 0.3$). Consequently, the net disposal of treated waste from plant 1 is reduced to only 20% of that in case 1 ($a_{21} = 0.2$). In addition, plant 1 sells 40% of its untreated waste as a renewable resource to the market ($a_{33} = 0.4$). Thus, the net disposal of untreated waste is reduced to 10% of that in case 1 ($a_{31} = 0.1$).

On the other hand, plant 2 sells its untreated waste in the form of nonrenewable resources to plant 1 as well as other entities in the market. The new marketable untreated waste stream is denoted as Y_{UW2} and has the coefficient of b_{32}. This stream is further divided into two substreams: one to plant 1 and the other to the market. The coefficients for these subdivided streams are b_{41} and b_{42}, respectively.

Because of the new demand for its untreated waste, plant 2 can increase the production of untreated waste (b_{11} is increased from 0.3 in both cases 1 and 2 to 0.5 in case 3) and directly sell the majority of it to the market without treatment ($b_{32} = 0.8$). In this case, the waste disposal for plant 2 is reduced to 20% of the total waste ($b_{31} = 0.2$ and $b_{21} = 0.2$). For the marketable waste from plant 2, plant 1 buys 50% ($b_{41} = 0.5$) and other plants buy the remaining 50% ($b_{42} = 0.5$).

Tables 4 and 5 give the index values for plants 1 and 2, respectively (see the last column of each table). The three indices, especially IEcP and ISP, are improved in case 3 as compared to the first two cases. The improvement in the economic (IEcP) and environmental (IEvP) performances of the plant is the result of (i) a realization of the market opportunities for the waste, (ii) a reduced investment in fresh resources, and (iii) a reduced waste disposal cost. The improvement in the environmental performance mainly is attributed to the following reasons: (i) a replacement of fresh nonrenewable/renewable resources by the waste exported from other plants and (ii) a further reduction in the net discharge of the waste into the environment.

Discussion. The case studies illustrated how to use these three indices to quantitatively analyze the sustainability of industrial systems. Under the conditions given in the case studies, the external recycle option (case 3) gives the best sustainability performance, followed by the one with internal recycle only (case 2), while the case without external or internal recycle (case 1) gives the worst performance. However, under a different scenario, for example, the recycle cost for waste is higher than the waste treatment cost, the comparison result may be different. Hence, the optimal strategy for maximizing sustainability depends on the various cost factors involved, and a general solution applicable to all cases cannot be arrived at.

Concluding Remarks

Through systematic consideration of the unique features of industrial systems, the newly developed indices, i.e., IEcP, IEvP, and ISP, can improve significantly the applicability of existing emergy-based sustainability indices. The new indices can be employed to effectively evaluate the economic, environmental, and eventually sustainability status of an industry or industrial ecosystem. This advancement brings deep insight into the sustainability issue of industrial systems and provides directions for the improvement of sustainability. Although the case study problem is relatively simple, the indices are, in principle, applicable to an industrial system of any complexity.

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Appendix: Mathematical Models for Plants

Mathematical Models for Plant 1.

Production and Waste Streams

$$M_{Y_{P1}} = 0.8X_1$$

$$M_{W1} = M_{W_{U1}} + M_{W_{T1}}$$

$$M_{W_{T1}} = M_{W_{TW1}} + M_{W_{TRN1}} + M_{Y_{TW1}}$$

$$M_{W_{U1}} = M_{W_{UW1}} + M_{W_{URR1}} + M_{Y_{UW1}}$$

$$M_{W1} = 1.4X_1$$

$$M_{W_{U1}} = a_{11}M_{W1}$$

$$M_{W_{T1}} = a_{12}M_{W1}$$

$$M_{W_{TW1}} = a_{21}M_{W_{T1}}$$

$$M_{W_{TRN1}} = a_{22}M_{W_{T1}}$$

$$M_{Y_{TW1}} = a_{23}M_{W_{T1}}$$

$$M_{W_{UW1}} = a_{31}M_{W_{U1}}$$

$$M_{W_{URR1}} = a_{32}M_{W_{U1}}$$

$$M_{Y_{UW1}} = a_{33}M_{W_{U1}}$$

$$M_{W_{RR1}} = M_{W_{URR1}}$$

$$M_{W_{RN1}} = M_{W_{TRN1}}$$

Constraints for the Coefficients of Waste Streams

$$a_{11} + a_{12} = 1$$

$$a_{21} + a_{22} + a_{23} = 1$$

$$a_{31} + a_{32} + a_{33} = 1$$

Money Value of the Streams or Investments

$$C_{F_{P1}} = 25 + 8.68{X_1}^{0.7}$$

$$C_{F_{W1}} = 2.5 + {M_{W_{TW1}}}^{0.6}$$

$$C_{F_{RR1}} = 25{M_{W_{RR1}}}^{0.5}$$

$$C_{F_{RN1}} = 25{M_{W_{RN1}}}^{0.5}$$

$$C_{F_{UD1}} = 15M_{W_{UW1}}$$

$$C_{F_{TD1}} = 10M_{W_{TW1}}$$

$$C_{R_1} = 30M_{R_1}$$

$$C_{N_1} = 45M_{N_1}$$

$$C_{N_{P1}} = 40M_{Y_{UW2A}}$$

Profit

$$P = 200M_{Y_{P1}} + 60M_{Y_{TW1}} + 40M_{Y_{UW1}} - 25 - 8.68 - {X_1}^{0.7} - 2.5 - {M_{W_{TW1}}}^{0.6} - 30M_{R_1} - 45M_{N_1} - 40M_{Y_{UW2A}} - 25{M_{W_{RR1}}}^{0.5} - 25{M_{W_{RN1}}}^{0.5} - 10M_{W_{TW1}} - 15M_{W_{UW1}}$$

Index of Economic Performance

$$\mathrm{IEcP} = (200 \times M_{Y_{P1}} + 60 \times M_{Y_{TW1}} + 40 \times M_{Y_{UW1}})/(25 + 8.68 \times X^{0.7} + 2.5 + M_{W_{TW1}}^{0.6} + 30 \times M_{R_1} + 45 \times M_{N_1} + 40 \times M_{Y_{UW2A}} + 25 \times M_{W_{RR1}}^{0.5} + 25 \times M_{W_{RN1}}^{0.5} + 10 \times M_{W_{TW1}} + 15 \times M_{W_{UW1}})$$

Index of Environmental Performance

$$\mathrm{IEvP} = (45M_{N_1} + 10M_{W_{TW1}} + 15M_{W_{UW1}})/(30M_{R_1} + 40M_{Y_{UW2A}} + 45M_{W_{RN1}} + 30M_{W_{RR1}})$$

Index of Sustainability Performance

$$\mathrm{ISP} = \mathrm{IEcP}/\mathrm{IEvP}$$

Mathematical Model for Plant 2.

Production and Waste Streams

$$M_{Y_{P2}} = 0.75X_2$$

$$M_{W2} = M_{W_{U2}} + M_{W_{T2}}$$

$$M_{Y_{T2}} = M_{W_{TW2}} + M_{W_{TRN2}} + M_{W_{TRR2}}$$

$$M_{W_{U2}} = M_{Y_{UW2}} + M_{W_{UW2}}$$

$$M_{Y_{UW2}} = M_{Y_{UW2A}} + M_{Y_{UW2B}}$$

$$M_{W_{RR2}} = M_{W_{TRR2}}$$

$$M_{W_{RN2}} = M_{W_{TRN2}}$$

$$M_{W2} = 1.35X_2$$

$$M_{W_{U2}} = b_{11} M_{W2}$$

$$M_{W_{T2}} = b_{12} M_{W2}$$

$$M_{W_{TW2}} = b_{21} M_{W_{T2}}$$

$$M_{W_{TRN2}} = b_{22} M_{W_{T2}}$$

$$M_{W_{TRN2}} = b_{23} M_{W_{T2}}$$

$$M_{W_{UW2}} = b_{31} M_{W_{U2}}$$

$$M_{Y_{UW2}} = b_{32} M_{W_{U2}}$$

$$M_{Y_{UW2A}} = b_{41} M_{Y_{UW2}}$$

$$M_{Y_{UW2B}} = b_{42} M_{Y_{UW2}}$$

Constraints for the Coefficients of Waste Streams

$$b_{11} + b_{12} = 1$$

$$b_{21} + b_{22} + b_{23} = 1$$

$$b_{31} + b_{32} = 1$$

$$b_{41} + b_{42} = 1$$

Investment

$$C_{F_{P2}} = 30 + 1.68 {X_2}^{0.7}$$

$$C_{F_{W2}} = 3 + {M_{W_{T2}}}^{0.6}$$

$$C_{F_{RR2}} = 10 {M_{W_{RR2}}}^{0.5}$$

$$C_{F_{RN2}} = 12 {M_{W_{RN2}}}^{0.5}$$

$$C_{F_{UD2}} = 40 M_{W_{UW2}}$$

$$C_{F_{TD2}} = 30 M_{W_{TW2}}$$

$$C_{R_2} = 50 M_{R_2}$$

$$C_{N_2} = 80 M_{N_2}$$

$$C_{N_{P1}} = 60 M_{Y_{TW1}}$$

Profit

$$P = 400 M_{YP_2} + 50 M_{Y_{UW2A}} + 50 M_{Y_{UW2B}} - 30 - 1.68 {X_2}^{0.7} - 3 - {M_{W_{TW2}}}^{0.6} - 50 M_{R_2} - 80 M_{N_2} - 60 M_{Y_{TW1}} - 10 {M_{W_{RR2}}}^{0.5} - 12 {M_{W_{RN2}}}^{0.5} - 40 M_{W_{UW2}} - 30 M_{W_{TW2}}$$

Index of Economic Performance

$$\mathrm{IEcP} = (400 M_{Y_{P2}} + 50 M_{Y_{UW2A}} + 50 M_{Y_{UW2B}}) / (30 + 1.68 Y^{0.7} + 3 + {M_{W_{TW2}}}^{0.6} + 50 M_{R_2} + 80 M_{N_2} + 60 M_{Y_{TW1}} + 10 {M_{W_{RR2}}}^{0.5} + 12 {M_{W_{RN2}}}^{0.5} + 40 M_{W_{UW2}} + 30 M_{W_{TW2}})$$

Index of Environmental Performance

$$\mathrm{IEvP} = (80 M_{N_2} + 40 M_{W_{UW2}} + 30 M_{W_{TW2}}) / (50 M_{R_2} + 60 M_{Y_{TW1}} + 80 M_{W_{RN2}} + 50 M_{W_{RR2}})$$

Index of Sustainability Performance

$$\mathrm{ISP} = \mathrm{IEcP}/\mathrm{IEvP}$$

In the models, X_1 is the amount of resources being processed in plant 1 (tons/year), X_2 is the amount of resources being processed in plant 2 (tons/year), M is the amount of the stream (tons/year), and C is the money value of the streams or investment ($/year).

In the calculation of the index values, the emergy value of each term is calculated based on its money value divided by the money-to-emergy ratio, $\xi = 1.75 \times 10^{12}$ SeJ/$.[10] Because ξ appears in both the numerator and denominator, eventually ξ is eliminated from the indices.

Nomenclature

F_D = total disposal cost
F_P = production cost
F_R = total cost for recycle
F_{RN} = cost for recycle of nonrenewable resources from waste
F_{RR} = cost for recycle of renewable resources from waste
F_{TD} = cost of disposing treated waste into the environment
F_{UD} = cost of disposing untreated waste into the environment
F_W = waste treatment cost
I = total resources consumed
N = nonrenewable resources
R = renewable resources
W = total waste generated during production
W_R = total recycled waste
W_{RN} = waste recycled as nonrenewable resources
W_{RR} = waste recycled as renewable resources
W_T = waste that should be treated
W_{TRN} = nonrenewable resource recycle from treated waste
W_{TRR} = renewable resource recycle from treated waste
W_{TW} = net discharge of treated waste into the environment
W_U = waste that can be disposed without treatment
W_{URN} = nonrenewable resource recycle from untreated waste
W_{URR} = renewable resource recycle from untreated waste
W_{UW} = net discharge of untreated waste into the environment
W_w = total waste discharge
Y_P = product yield
Y_{TW} = yield from treated waste
Y_{UW} = yield from untreated waste
Y_W = total marketable waste

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